A HIERARCHICAL EXPLORATION OF HOW DESIGN MARGINS ENABLE ADAPTABILITY

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ABSTRACT

Our society is built on engineered systems. Engineers are becoming increasingly concerned with the sustainability of systems, particularly their ability to adapt to a changing world. Recently, there has been increased interest in exploring how design margins provide opportunities for a system change. There have been great developments in determining how design margins can absorb change at a system level, but it is still not clear how design margins might provide change opportunities at a decision variable level. In this paper, we show how system-level margins could be deconstructed to explore what change opportunities they may provide at a decision variable level. We also investigate how the coupling of functional requirements limits how system-level margins can be operationalized. Our analysis suggests that design margins can provide meaningful change opportunities at the decision variable level, but the mechanisms that produce these opportunities are complex. These insights lay the groundwork for future research on mapping and representing design margins in the context of system adaptability.

Keywords: Product architecture, Large-scale engineering systems, Requirements, System evolvability, Margin

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1 INTRODUCTION

Engineered systems are the backbone of our technological society. We believe that the future's successful engineered systems will be those than can adapt to changing requirements and new use cases. This ability to adapt—or evolve, depending on the paper that is describing the process—will be a necessary property because of our inability to accurately predict the future. Products and systems that operate in a changing world and lack the ability to adapt will offer decreased value propositions. Further, even when our forecasts turn out to be correct, engineers will envision ways that a system will need to accommodate new technologies. Research focused on system changeability (Schulz et al., 2000) and the entire set of -ilities (Chalupnik et al., 2013; Ross et al., 2008)—including, but not limited to, flexibility (Ferguson et al., 2007; Hu and Cardin, 2015; Knight et al., 2015; Saleh et al., 2003; Sapol and Szajnfarber, 2020; Tilstra et al., 2015), adaptability (Engel and Browning, 2008; Engel and Reich, 2015; Madni, 2012), and evolvability (Allen et al., 2017; Cansler et al., 2016; Luo, 2015)—explores ways that engineering designers can positively impact the value of a complex system, particularly one that will be used in the built environment (energy, transportation, etc.) in response to uncertain futures.

The case for designing systems that can be modified after their deployment has also been supported by research in modularity (ElMaraghy and AlGeddawy, 2015; Pakkanen et al., 2016), architecture definition (van Beek and Tomiyama, 2012; Browning et al., 2001; Keese et al., 2006; Luo, 2015), and change propagation (Ahmad et al., 2013; Pasqual and de Weck, 2012). Recently, there has been increased interest in the role that design margins play in the design process, and how margins provide opportunities for changing a designed system after it has been deployed. Design margins, included within a system for both deliberate and indeliberate reasons, can be used by design engineers to tackle known and unknown risks and various kinds of uncertainties (Eckert et al., 2019). While margins have a long history in the engineering design process, Eckert and Isaksson highlight their "hidden" nature. Documentation, acknowledgement, and communication of margins is often ad hoc at best and unacknowledged at worst.

This paper contributes to the growing research focused on improving our understanding of, and processes for, modelling, documenting, and analysing margins. Research studies have described how margins can be part of the process for selecting a jet engine material when considering temperature (Eckert et al., 2019), sizing an airplane with respect to the requirement of payload weight (El Fassi et al., 2020), the design of three components of a hydraulic circuit (Brahma and Wynn, 2020), and pre-design sizing of a car battery with respect to a requirement on engine cranking (Touboul et al., 2019). These research efforts have developed insights into the role of margins and have demonstrated the potential of margins at reducing change propagation and enabling adaptation. However, the mechanisms by which margins are understood in complex and coupled systems require additional research. In this paper, we discuss challenges of modelling and analysing margins when considering a system that has multiple coupled functional requirements. We also describe the challenges and provide some early insights into how margins can be represented and operationalized at the level of a decision variable.

2 MATHEMATICAL DEFINITION OF MARGIN

Eckert et al. define margin as "the extent to which a parameter value exceeds what it needs to meet its functional requirements regardless of the motivation for which the margin was included." (Eckert et al., 2019) Eckert and Isaksson also establish that design margins—the focus of this paper—are different than the well-established notion of safety margins (Eckert and Isaksson, 2017). While safety margins are embodied in the requirements of a system as a hedge against uncertainty during the use phase, design requirements are associated with the uncertainties that arise throughout the design process (including modifications to a system after it has been put into the field). The definition of margin posed by Eckert et al. can be further refined by considering the following concepts:

1. **Requirements**: the values parameters need to reach (must be inequalities).
2. **Constraints**: bounds on the values that a parameter can take on.
3. **Capability**: the values that a parameter can reach regardless of constraints or requirements.

The key difference between constraints and requirements is that requirements are stated independent of the final solution. Conversely, constraints are established by the embodiment of the specific solution. Given this definition, requirements establish functional and system-level specifications,

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while constraints are derived from an architecture's structure and interfaces. Building on these concepts, a mathematical description of margin is provided in Equation 1.

$$M(P) = \min\{|Cap(P) - R(P)|, |Cap(P) - Const(P)|\} \tag{1}$$

The margin, $M(P)$, on a parameter, P, is calculated as a function of a system's capability for a parameter, $Cap(P)$, and requirements and constraints on P, $R(P)$ and $Const(P)$ respectively. In this paper, we define a parameter as a feature of a design that is governed by requirements or constraints, and we model parameters as functions of one or more decision variables (DVs). For a given parameter, using the mathematical definition provided in Equation 1, "margin is the useable difference between capabilities, requirements, and constraints" (Eckert et al., 2019). The minimization operator ensures that the margin is usable. By taking the minimum difference between capabilities and requirements and capabilities and constraints, a margin represents the most that a relevant capability, requirement, or constraint could change while maintaining solution feasibility.

While the literature on design margins often describes how and why margins are incorporated during the process of designing, we are particularly interested in the role of margins in the context of adaptability. Adaptability refers to the physical change of a system via modification after it has been deployed. In these cases, margins absorb the ramifications of the changes made within the system and limit the extent of change propagation that occurs. Change propagation, therefore, is limited because margins are consumed without violating a requirement or constraint.

A series of simple scenarios are illustrated in Figure 1 to depict how margins absorb, or fail to absorb, the ramification of a modification in response to a change in requirement or capability. The top two illustrations represent cases where changes are absorbed by margin, and the margin on the parameter is reduced. The bottom two illustrations depict changes that cannot be absorbed by margin, and a deficit exists between the capability of the parameter and the requirement on the parameter. A deficit represents infeasibility. Design changes must be made to ensure that the parameter capability is feasible with respect to the relevant requirement. As such, the bottom two cases illustrate when change will propagate.

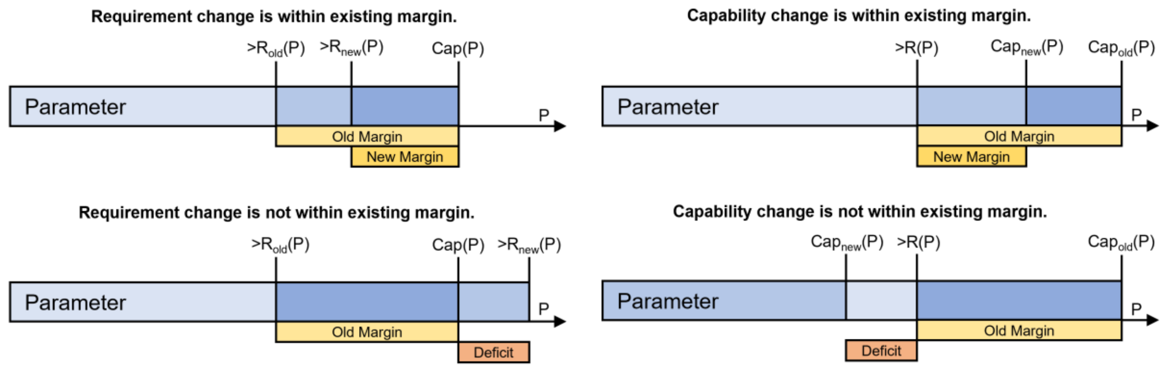

Figure 1. Illustrations of how margins can, or fail to, absorb a change in a parameter.

The mathematical definition for margin posed in Equation 1, however, is limited in scope to the one-time change in parameter capability or requirements. When the initial change cannot be absorbed by margin, it is simple to say that a parameter capability must change to ensure that a system remains feasible. Yet, realizing a change in a parameter capability can be difficult. It is also not clear how margins can be used to further limit change propagation. This is because parameters (system attribute/property) may be related to many decision variables, and decision variables (DVs) may be related to many parameters (coupling).

3 CHALLENGE #1: LINKING DECISION VARIABLES, MARGINS, AND SYSTEM-LEVEL CONSEQUENCES

The one-to-many mapping from parameters to decision variables gives engineers (at least some) design freedom when determining how a chance can be accommodated. However, evaluating the

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system-level consequences of each modification can be a challenge. While margins offer the ability to limit change propagation during a modification, it is unclear how parameter margins can be used strategically at a component level. This makes it difficult to identify the most favourable (optimal) modification. When adapting a system, it may be favorable to accommodate a modification that requires the least amount of change. Other perspectives could win out here too, as it may be desirable to accommodate multiple (future) changes and/or the difficulty associated with making the change might be considered. We need to develop a better understanding of how margins on parameters can be operationalized at the level of decision variables so that change consequences can be limited.

3.1 Exploring the margin on drift distance for a high-powered rocket

We have previously explored the ramifications of adapting a high-powered model rocket constructed by an NC State student team (Jacobson and Ferguson, 2022). In that paper we focused on the recovery system and revisit this example because the coupling within a rocket's recovery system makes adaptation challenging. Our original model of the rocket's architecture uses a dual-deploy recovery architecture. That is, a drogue parachute deploys at a specified time after apogee to initially slow the vehicle. After the vehicle has descended to a specified altitude, the main parachute deploys and slows the vehicle to its landing speed. Engineering designers control the sizing of each parachute, the drogue deployment delay time, and main parachute deployment altitude. The recovery system is tuned to meet multiple requirements, with some of the most important being the vehicle's kinetic energy upon landing, descent time, and drift distance. These requirements are established by the competition sponsor.

Our example will follow an adaptation related to drift distance. Requirements established by the project sponsor impose a maximum allowable drift distance, and this requirement may change if a vehicle is launched on a smaller launch field. While the rocket configuration meets the original drift requirement, and the current capability provides margin, the magnitude by which the requirement changes, and how that margin is consumed, influences feasibility. We illustrate each case in Figure 2, where on the right, the requirement changes to such an extent that all margin is consumed, and a deficit remains. That is, the design is infeasible and further changes must be made.

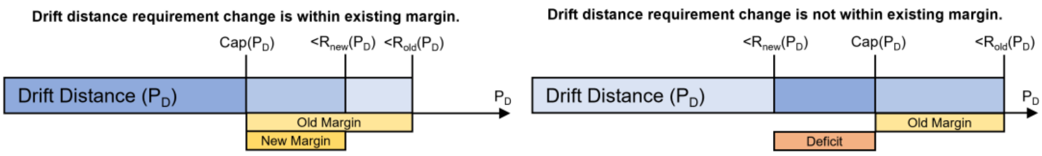

Figure 2. Illustrating how margin could, or could not, absorb a change in drift distance.

Drift distance is a function of many DVs, including drogue parachute (DP) drag properties, main parachute (MP) drag properties, deployment altitudes, deployment delays, and vehicle burnout weight. A block diagram illustrating these relationships is shown in Figure 3, where DVs are shown in yellow and the parameter of interest is bolded in a blue block. The modification of each DV in the diagram alters the rocket's drift distance and can also further propagate change in unique ways. Four of the DVs, for example, are within the recovery subsystem: DP drag properties, MP drag properties, drogue delay, and MP deployment altitude. Each DV also relates to several other parameters, as depicted in Figure 4. The relationships between DVs and parameters impacts the likelihood that the modification of a DV may propagate change through parameters. Margins, if incorporated into the various related parameters, could provide greater ability to modify components without change propagating.

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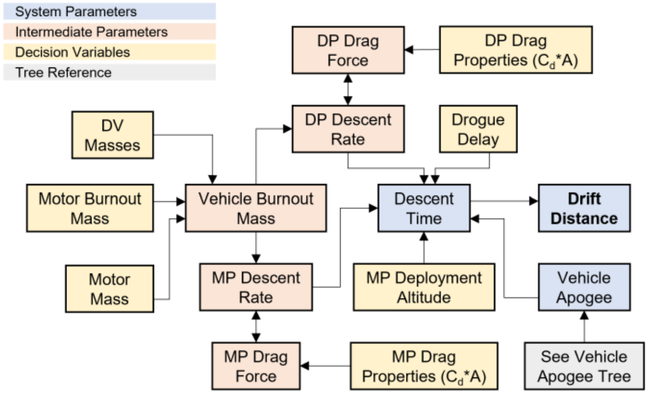

Figure 3. A system map illustrating the relationships between decision variables (yellow) and drift distance (blue)

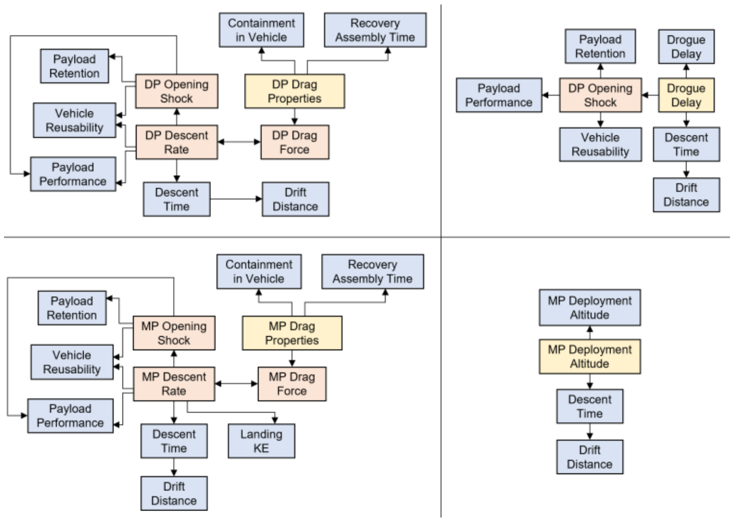

Figure 4. System maps illustrating ways in which the decision variables that impact drift distance are coupled to other system parameters.

3.2 Highlighting the challenges of margin consumption during a redesign

Parameter capabilities are changed by modifying DVs. It is important to define relationships between parameters and DVs so that the strategic use of parameter margins at the DV level can be explored. In cases where a parameter is a function of multiple DVs (which we posit to be true in almost all cases), adjusting the capability of a parameter can be achieved in multiple ways. This is how engineers get the freedom to choose what relevant DVs to modify. Determining a DV modification strategy can be difficult because each DV modification has its own set of complex consequences, given that changes can propagate many ways in a highly-coupled system. Scenarios for the change consequences when a parameter margin is consumed in response to an initiating change are described in Figure 5:

- **Scenario 1:** The margin on the parameter can absorb the change.
  - When a requirement change can be absorbed by a parameter margin, no system modification is required, but margin on the relevant parameter will be altered.
- **Scenario 2:** If the parameter margin is not large enough to accommodate the redesign, many parameter capabilities and margins can be altered, and change can propagate in many ways.
  - As a DV is modified to accommodate a change to a requirement on parameter P_1, the value of P_1 is changed. If P_1 becomes feasible, a new margin on P_1 is established.
  - If the DV modification was not sufficient to make P_1 feasible, additional DVs must be modified.
  - If the modified DV is coupled to other system parameters, the value of those parameters will change. Then, as a knock-on effect, the margins on these parameters will change. This provides a potential for change to propagate through related parameters. If the other

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parameters associated with the DV become infeasible, change would further propagate through requirements. Additional DVs must be modified to return the system to a feasible state.

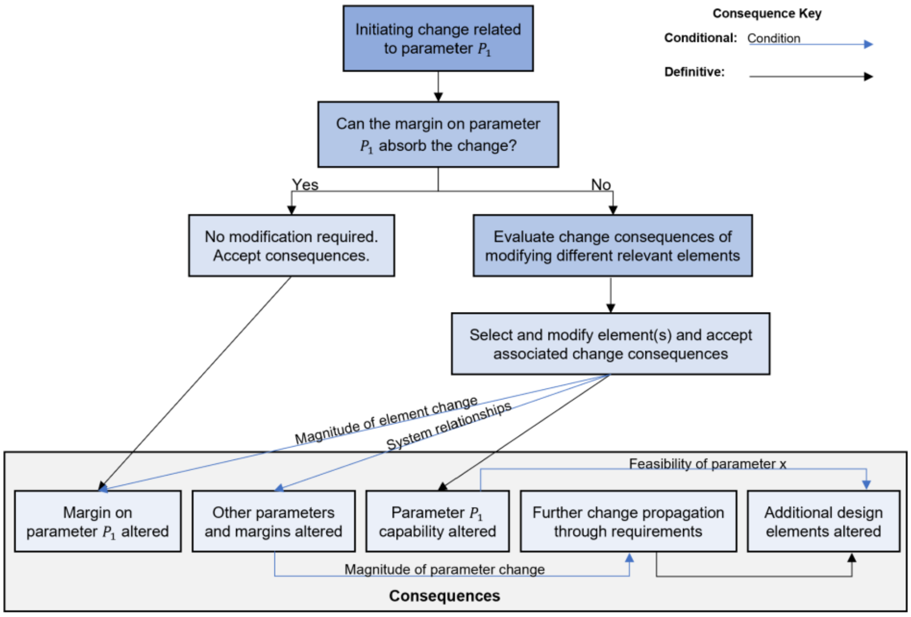

Figure 5. Decision tree illustrating how the consequences of a redesign expand when the margin on a parameter cannot absorb the change.

From this exploration we also gain insight into "lines of defense" against change propagation. Parameter margin is the first line of defense. If there is sufficient parameter margin, the relevant parameter margin is altered but change does not propagate. Otherwise, a DV must be modified to accommodate a change. A DV with a small amount of coupling (strategically or by happenstance) is the second line of defense. If a DV is only related to one parameter, the DV can be easily modified to accommodate the change. As a result, the capability of the relevant parameter is changed, and the margin on the relevant parameter is changed, but change does not propagate further. Finally, if a DV is coupled, it has the potential to propagate change through other related parameters as it is modified. Preventing this propagation to other parameters may be desirable, as this would be a third line of defense against change propagation. We hypothesize that this third line of defense may exist when there is sufficient parameter margin in all parameters related to DVs.

We return to the rocket example to describe what lines of defense against change propagation may exist in a real system. In the scenario where the requirement on maximum drift distance is reduced:

- **First line of defense:** There is significant margin on drift distance. The rocket's initial drift distance was significantly below the initial requirement. The rocket's drift distance is still below the maximum drift distance imposed by the new requirement. This results in a reduction of drift distance margin, but no DVs in the recovery subsystem need to change.
- **Second line of defense:** In reality, there are no DVs in the recovery system that are uncoupled. The MP deployment altitude is the least coupled, only relating to three parameters. If the MP deployment altitude were only related to drift distance, the deployment altitude could be changed without propagating change to another parameter.
- **Third line of defense:** DP drag properties are related to six parameters in addition to drift distance. If DP drag characteristics are changed, there is a potential for change to propagate through up to six parameters. However, if there is a large range that DP drag characteristics could change before making related parameters infeasible, DP drag could be modified greatly, providing a wide range of drift distance performance options, without propagating change. This may occur when there is significant margin in each of the six parameters relating to DP drag properties.

We foresee many design scenarios that require us to use the "third line of defense". That is, multiple decision variables will be changed, and multiple parameters will be impacted. This motivates the need for quantifying a usable margin on DVs. We define usable margin of a DV as the extent to which a DV can be modified so that a parameter change can be accommodated while maintaining solution feasibility.

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In the next sections, we show that usable margin can be represented as a deconstruction of parameter margins, thereby demonstrating how parameter margins could stop change propagation at a DV level.

4 CHALLENGE #2: EACH DECISION VARIABLE CAN IMPACT THE CAPABILITY OF MULTIPLE SYSTEM PARAMETERS

Much of the existing research on margins is focused on a single system requirement. As multiple requirements comprise system design, a DV may be associated with multiple margins—one for each requirement and constraint that it maps to. This coupling further influences how much a DV can be modified before change propagates. Determining the usable margin of a decision variable is accomplished by defining state specific-constraints. State-specific constraints (S) establish bounds on a DV with respect to a single requirement in the existing system state.

A requirement is translated into a state-specific constraint on a DV by determining the extent to which the DV could independently change without making the design solution infeasible with respect to the requirement. Specifically, state-specific constraints can be derived by sweeping DVs with respect to system parameters, as is done in sensitivity analysis. The range over which a DV is feasible with respect to a given requirement is calculated from the DV sweeps, defining the state-specific constraint.

Margins on a DV can then be calculated from the state-specific constraints. We depict in Figure 6 how multiple margins overlap for a specific decision variable—denoted by the variable e to distinguish it from the rest of the decision variables. The usable margin on a DV is determined by taking the minimum of its DV margins. The yellow bars in the figure represent DV margins derived from state-specific constraints. The orange box shows the usable margin – the common range covered by the yellow bars.

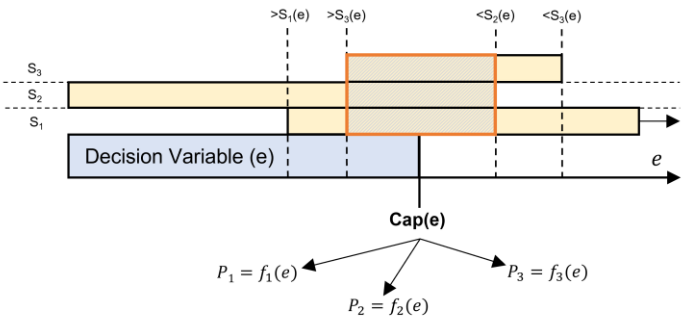

Figure 6. Margins on a DV with respect to state-specific constraints

To capture the full range over which a DV could change, state-specific constraints that place upper and lower bounds on a DV can be separated. We designate the lower usable margin on a DV as the consumable margin and the upper usable margin as the expandable margin. Together, these represent the usable margin on the DV, as depicted in Figure 7.

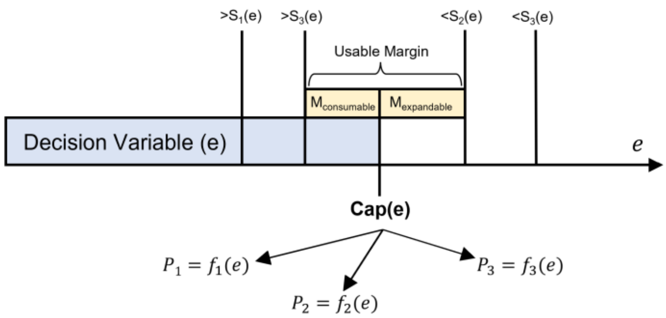

Figure 7. Usable margin on a DV derived from state-specific constraints.

In the context of the rocketry problem, usable margins can be determined for each of the DVs in the recovery subsystem, as shown in Figure 8. Each DV has an upper and lower bound in the current system state as derived from relationships to system parameters, limiting the extent to which the DVs can be modified before change propagates. For example:

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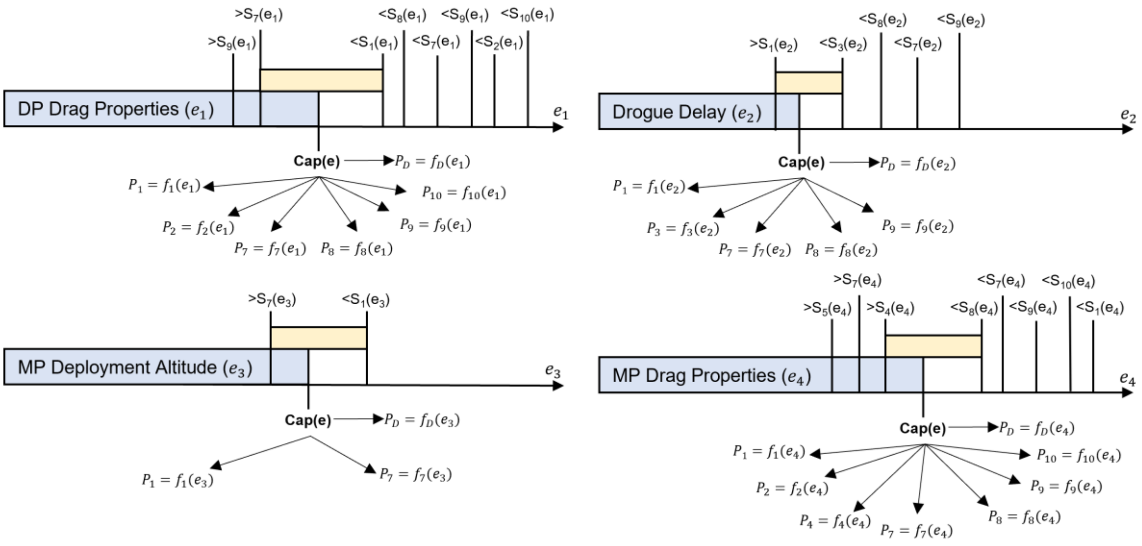
- The drogue parachute’s drag properties could decrease to reduce drift distance, but this could result in the payload performance parameter and vehicle reusability parameter becoming infeasible.
- Main parachute drag properties could also be decreased but only to a certain extent before the landing kinetic energy parameter becomes infeasible.
- The drogue delay and the main parachute deployment altitude relate to fewer parameters, so it may be easier to modify them. However, these DVs are also bounded by requirements for safety purposes, and these bounds substantially limit what can be done with these DVs.



Specification and Parameter Key						DV Key	
Drift Distance	S_D, P_D	Landing kinetic energy	S_4, P_4	Payload retention	S_8, P_8	DP Drag Properties	e_1
Descent time	S_1, P_1	MP containment in vehicle	S_5, P_5	Vehicle reusability	S_9, P_9	DP Deployment Delay	e_2
DP containment in vehicle	S_2, P_2	MP deployment altitude	S_6, P_6	Recovery assembly time	S_{10}, P_{10}	MP Deployment Altitude	e_3
DP deployment delay	S_3, P_3	Payload performance	S_7, P_7			MP Drag Properties	e_4

Figure 8. State-specific feasible ranges for recovery DVs.

Given the coupling between the recovery subsystem DVs and system parameters, it is challenging to determine what DV should be modified if the drift distance requirement changes. The decomposition of parameter margin into the usable margins offers some perspective about opportunities that could be pursued for a one-time change. Yet, it is still difficult to determine what DV, or set of DVs, should be altered, especially considering that these usable margins only show a fraction of the redesign landscape, as the modelling of usable margins in this study is not exhaustive. Calculating the usable margin on additional DVs in the system would reveal more change pathways. An additional complexity is that although exceeding the usable margins guarantees that change will propagate through other parameters, this might result in a more efficient change pathway overall.

Extending the recovery system analysis, other elements that influence drift distance include vehicle apogee and mass. These elements provide additional options for responding to a design change. In a more thorough mapping, these elements could be broken down into specific DVs, such as the mass of each component and the motor’s thrust properties. An analysis involving component masses would reveal more change pathways, but it would also reveal more coupling, given that component masses are related to many vehicle performance and stability requirements.

5 DISCUSSION AND CONCLUSIONS

We highlight two pressing challenges associated with the modelling and analysis of margins for the adaptation of engineered systems. In Section 3, we draw attention to the issue that design margins are often considered, or generally understood, at the parameter level. As parameters are a function of multiple decision variables, the coupling between decision variables, requirements, and system parameters must be (fully) understood. Using the example of a high-powered rocket, we demonstrate

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how a single parameter (drift distance) is a function of at least four decision variables associated with the recovery stage (main parachute drag properties, drogue parachute drag properties, main parachute deployment altitude, and drogue delay) and could be extended to encompass the mass of each component (in an extreme, perhaps worst-case scenario). We acknowledged that modifying a single DV could, at times, achieve the desired modification of the system parameter. However, we expect that this will occur infrequently, at least without propagating change through other related parameters. By considering ways that change could propagate, we identified three "lines of defense" against change propagation: 1) parameter margins, 2) taking advantage of uncoupled DVs, and 3) modification of each DV within its "usable margin". Usable margin is related to the first two lines of defense in that it is derived from decomposed parameter margins and an understanding of the DV-parameter relationships.
In Section 4, we describe how the concept of usable margin is a first step toward exploring how a parameter margin may be decomposed and operationalized to limit change propagation. Deriving usable margin requires the definition of a current system state and an analysis of how much each DV can change before margin is consumed and constraints or requirements are violated. We highlight the coupling that is present, not only between DVs but in the fact that each DV can influence multiple parameters, and how the constraints associated with those parameters creates an effective usable margin. This makes sequential modification of a system extremely difficult to design for and suggests that thoughtful consideration of how margins are consumed will be important in preserving the ability to adapt.
The analysis presented in this paper draws attention to the difficulty of modelling, analysing, and consuming margin when considering specific decision variables. Going forward, there is a need for the development of design processes and design tools that will enable us to effectively model and communicate margins so that they can be operationalized by members of a design team. Our proposed concept of a "usable margin" is a first step toward exploring how a parameter margin may be decomposed and modelled so that it can be operationalized. We hypothesize that documentation and communication of usable margins could prevent designers from propagating change unintentionally and could reveal opportunities for strategic system adaptation. However, we acknowledge a limitation in that our definition only describes how parameter margins can be used with respect to individual DVs. It is often advantageous to modify a set of DVs to accommodate a change. Additional work is needed to improve our process of mapping parameter margins to DVs.
In drawing our conclusions, we also identify other research directions around margin and change propagation that require further exploration:

- It is challenging to determine how parameter margins effectively limit change propagation. What types of modelling approaches around margin decomposition are needed so that DV-parameter relationships can be better understood in the context of margin in highly coupled systems?
- What is the most effective initial placement of margins so that we have the most robust lines of defense against change propagation?
- What are the most effective ways of structuring a system architecture so that coupling is minimized, performance impacts are managed, and the second line of defense (taking advantage of a one-to-one mapping) is enabled?
- Even if we can build in lines of defense against change propagation as part of the original system design, these lines of defense may be greatly reduced or eliminated once the first modification is made. How can these lines of defense be preserved to enable future adaptability?

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